Microlensing Exoplanet Mass Measurement in WFIRST Era

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Know Thy Star, Know Thy Planet
October 12, 2017
Importance of Mass Measurements from Microlensing

Study the wide orbit exoplanets beyond snow line as a function of their host star mass and separation since:
- according to core accretion it is the birthplace of planet formation
- a possible origin of the water in habitable zone

Mass measurements and upper limits of wide orbit exoplanets down to earth mass with WFIRST including solar system analogs.

Study planet population and verify planet formation

Galactic distribution of exoplanets towards galactic center.

Suzuki+ 2016, Suzuki+ 2018 in prep

Photo credits: D. Bennett, M. Penny
Planetary Microlensing Events with Physical Parameters

OGLE-2003-BLG-235 (Bennett+ 2006)
OGLE-2005-BLG-071 (Dong+ 2009, Udalski+ 2006)
OGLE-2006-BLG-109 (Gaudi+ 2010)
OGLE-2007-BLG-368 (Sumi+ 2010)
MOA-2007-BLG-400 (Dong+ 2009a)
OGLE-2007-BLG-349 (Bennett+ 2016)
MOA-2008-BLG-310 (Bhattacharya+ 2017, Janczak+ 2010)
MOA-2009-BLG-319 (Miyake+ 2011)
MOA-2011-BLG-293 (Batista+ 2014, Yee+ 2012)
OGLE-2012-BLG-006 (Poleski+ 2017)
OGLE-2012-BLG-0950 (Koshimoto+ 2016)
OGLE-2012-BLG-563 (Fukui+ 2015)
OGLE-2012-BLG-0026 (Beaulieu+ 2016)
MOA-2013-BLG-220 (Yee+ 2014)
OGLE-2013-BLG-605 (Sumi+ 2016)
MOA-2016-BLG-227 (Koshimoto+ 2017b)
OGLE-2016-BLG-1195 (Yossi+ 2017, Bond+ 2017)
A typical case of microlensing light curve modelling provides with planet-host star mass ratio $q$ and planet – star separation $s$ in Einstein radius. But does NOT provide planet, host star masses and distances in physical values.

If lucky, parallax measurements from ground and SPITZER can provide us mass and distance measurements.

We need high resolution images to get mass measurements.
Mass Measurements with Follow-Up High Resolution Images

• Mass Measurement using isochrones – C.Henderson Talk

• Mass measurement with lens detection using PSF fitting

We need from light curve fitting:
  o Angular Einstein radius ($\theta_E$)
  o Planet-host star mass ratio (q)
  o Planet- star separation in Einstein radius units (s)
  o Lens-source relative proper motion ($\mu_{\text{rel}}$)
Finite Source Effects & Lens Brightness Measurement Yield Lens System Mass

- Finite source effect or lens-source proper motion
  Angular Einstein radius $\theta_E = \theta_* t_E / t_*$
  $\theta_* =$ source star angular radius
  $D_L$ and $D_S$ are the lens and source distances

- Lens brightness & color(AO,HST) used in
  Mass- Luminosity relation
  mass-distance relation $\Rightarrow D_L, M_L$

\[ M_L = \frac{c^2}{4G} \frac{\theta_E^2}{D_S D_L} \frac{D_S D_L}{D_S - D_L} \]
\[
\theta_E^2 = \frac{4GM_L(D_S-D_L)}{c^2D_SD_L}
\]

Mass – Luminosity Empirical relation \(^1,2,3,4\)

From PSF fitting to HST image
Constrains \(I_s\) and total target brightness

\(\theta_E\) from light curve models

\(D_S \sim 8 \text{kpc}\)
\(a_\perp = \theta_E s D_L\)
\(\theta_E\) , \(s\) (known from light curve model)

\(M_L = M_P + M_H\)
\(q = M_P / M_H\)

Input 1 a
\(\theta_E\) from light curve models

Output 1
\(M_H, M_P\)

Output 2
\(D_L, a_\perp\)

Input 2 a
\(M_L\)
\(D_L/D_S\)

Input 2 b

Final Results
Input 2 b

Stage 1
Stage 2
Stage 3

Input 1 b
From PSF fitting to HST image
Constrains \(I_s\) and total target brightness

HST Observations & PSF Fitting

First Direct Relative (Lens-Source) Proper motion of Planetary Microlens Host Star Measured

Follow–Up Observations of OGLE-2005-BLG-169 taken 6.5 years after the peak

\[ \mu_{\text{rel,}} = 7.39 \pm 0.20 \text{ mas/yr} \]

\[ \mu_{\text{rel,}} = 1.33 \pm 0.23 \text{ mas/yr} \]
HST Observations & PSF Fitting

First Direct Relative (Lens-Source) Proper motion of Planetary Microlens Host Star Measured

\[ \mu_{\text{rel}_I} = 7.39 \pm 0.20 \text{ mas/yr} \]
\[ \mu_{\text{rel}_B} = 1.33 \pm 0.23 \text{ mas/yr} \]

Lens Source brightness similar in I band indicating Lens redder than source hence Lens is also fainter in V and B band
\[ \theta_E^2 = \frac{4GM_L(D_S - D_L)}{c^2D_SD_L} \]

Mass – Luminosity
Empirical relation

\[ M_L = M_P + M_H \]
\[ q = \frac{M_P}{M_H} (6 \times 10^{-5}) \]

From PSF fitting to HST image
Constrains \( I_s \) and total target brightness

\[ D_S \approx 8 \text{kpc} \]
\[ a_\perp = \theta_E s D_L \]
\[ \theta_E, s \text{ (known from light curve model)} \]

Input 1 a
\( \theta_E \) from light curve models

Stage 1

Input 2 a

Final Results

Output 1
\( M_H, M_P \)

Output 2
\( D_L, a_\perp \)

Stage 2

Stage 3

Input 2 b

OGLE-2005-BLG-169: HST & Keck

HST

- \( \mu_{\text{rel}_l} = 7.39 \pm 0.20 \text{ mas/yr} \)
- \( \mu_{\text{rel}_b} = 1.33 \pm 0.23 \text{ mas/yr} \)

Keck

- \( \mu_{\text{rel}_l} = 7.28 \pm 0.12 \text{ mas/yr} \)
- \( \mu_{\text{rel}_b} = 1.54 \pm 0.12 \text{ mas/yr} \)

Both supports \( \alpha \sim 90^\circ \) and \( q = 6 \times 10^{-5} \) model

- Host mass: \( 0.687 \pm 0.021 \, M_\odot \)
- Planet Mass: \( 14.1 \pm 0.9 \, M_\oplus \)
- \( D_L = 4.1 \pm 0.4 \, \text{kpc} \)
- Projected Separation\( (a_{\perp}) \): \( 3.5 \pm 0.3 \, \text{AU} \)

- Host mass: \( 0.667 \pm 0.049 \, M_\odot \)
- Planet Mass: \( 13 \pm 1.5 \, M_\oplus \)
- \( D_L = 3.9 \pm 0.4 \, \text{kpc} \)
- Projected Separation\( (a_{\perp}) \): \( 3.4 \pm 0.3 \, \text{AU} \)

8.3 years after discovery\(^1\)

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Ideal condition of Follow up Observations for Mass Measurement

Cannot confirm the lens—too early

Best Condition

Which one is lens? Lens or ambient star? too late

GAIA cannot do this because: PSF fitting
We absolutely need **high resolution follow up** for the current ground based planetary microlensing

In future with WFIRST Space Based Microlensing Survey we will be able to measure mass directly from the survey with lens detection
Planetary Microlensing Events with Excess Flux Detection in High Resolution Images

MOA-2008-BLG-310 (Janczak+ 2010, Bhattacharya+ 2017)
MOA-2011-BLG-293 (Batista+ 2014, Yee+ 2012)
OGLE-2012-BLG-0950 (Koshimoto+ 2016)
OGLE-2012-BLG-563 (Fukui+ 2015)
OGLE-2007-BLG-368 (Sumi+ 2010)
OGLE-2007-BLG-349 (Bennett+ 2016)
OGLE-2012-BLG-0026 (Beaulieu+ 2016)
OGLE-2006-BLG-109 (Gaudi+ 2010)
OGLE-2003-BLG-235 (Bennett+ 2006)
OGLE-2005-BLG-071 (Dong+ 2009, Udalski+ 2006)
**MOA-2008-BLG-310**

- From Discovery paper:\(^1\):

  \[ q = (3.3 \pm 0.3) \times 10^{-4} \]

  Sub Saturn mass planet

  \[ \mu_{\text{relG}} = 5.1 \pm 0.3 \text{ mas/yr} \]

- Excess flux in H band (NACO Data)

- Extra Flux detected on top of source in HST I and V band data in both epochs 3.6 and 5.6 years later

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MOA-2008-BLG-310
Two star fit – Source Flux Constrained

Source Flux constrained from light curve fitting

Bhattacharya+ 2017
## MOA-2008-BLG-310

### Two star fit – Source Flux and Lens- Source Separation Constrained

<table>
<thead>
<tr>
<th>Dual Star Fit</th>
<th>Year</th>
<th>Filter</th>
<th>Magnitude*</th>
<th>Separation</th>
<th>Separation star 2 - star 1</th>
<th>$\chi^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Star 1</td>
<td>Star 2</td>
<td>(mas)</td>
<td>$\Delta x$</td>
</tr>
<tr>
<td>Best Fit</td>
<td>2012</td>
<td>$I$</td>
<td>19.84(0.15)</td>
<td>20.31(0.24)</td>
<td>14.1(3.2)</td>
<td>9.5(2.6)</td>
</tr>
<tr>
<td></td>
<td>2014</td>
<td>$V$</td>
<td>21.37(0.18)</td>
<td>21.74(0.56)</td>
<td>15.2(2.9)</td>
<td>6.7(2.5)</td>
</tr>
<tr>
<td>Source Flux</td>
<td>2012</td>
<td>$I$</td>
<td>19.86(0.14)</td>
<td>20.28(0.18)</td>
<td>12.2 (3.3)</td>
<td>10.6(1.8)</td>
</tr>
<tr>
<td>Constrained</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Source Flux</td>
<td>2014</td>
<td>$V$</td>
<td>21.47(0.22)</td>
<td>21.64(0.27)</td>
<td>11.6(3.7)</td>
<td>10.3(2.2)</td>
</tr>
<tr>
<td>and Separation</td>
<td>2012</td>
<td>$I$</td>
<td>19.47(0.05)</td>
<td>21.35(0.29)</td>
<td>16.6(2.1)</td>
<td>11.2(1.2)</td>
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<tr>
<td>Constrained</td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Source Flux</td>
<td>2014</td>
<td>$V$</td>
<td>21.11(0.12)</td>
<td>22.26(0.38)</td>
<td>16.1(2.9)</td>
<td>9.2(2.1)</td>
</tr>
<tr>
<td>and Separation</td>
<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

This Table presents magnitudes calibrated to the OGLE-III scale.

\[\chi^2\] is high

Aparna Bhattacharya
Two star fit – Conclusions

- The Extra flux on top of the source is primarily NOT due to the lens
- Source Companion – The velocity of the blend star is too high to be source companion
- Lens Companion – Velocity measurement is not similar to lens– not a lens companion
- Ambient Star – Possibly, the proper motion is consistent with bulge stars
Two star fit – Conclusion
The Excess Flux is not necessarily due to the lens primarily.
It is important to verify the lens with the lens-source relative proper motion.

Three star fit – Upper Limit on Lens Mass
Three star fit – Upper Limit on Lens Mass

<table>
<thead>
<tr>
<th>parameter</th>
<th>units</th>
<th>99% confidence</th>
<th>95% confidence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Host star mass, $M_*$</td>
<td>$M_\odot$</td>
<td>0.64</td>
<td>0.73</td>
</tr>
<tr>
<td>Planet mass, $m_P$</td>
<td>$M_\oplus$</td>
<td>72</td>
<td>82</td>
</tr>
<tr>
<td>Host star - Planet 2D separation, $a_\perp$</td>
<td>AU</td>
<td>1.1</td>
<td>1.1</td>
</tr>
<tr>
<td>Lens distance, $D_L$</td>
<td>kpc</td>
<td>7.8</td>
<td>7.8</td>
</tr>
</tbody>
</table>

$I = 22.15, V = 23.41$ (99% confidence)

$I = 22.44, V = 23.62$ (95% confidence)

Bhattacharya+ 2017
Conclusions

• Space based microlensing survey like WFIRST will be able to not only detect the microlensing exoplanets but will also measure the mass of the exoplanets directly from the survey.

• Extra Flux detection on top of the source is not necessarily the lens. We have to be careful to verify the lens with relative proper motion in high resolution images.

• We can still get an upper limit on the mass measurements.
Thank You